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13. ABSTRACT *(Maximum 200 words)*

The foundations of the modern theory of sound propagation and scattering in a homogeneous and isotropic atmospheric turbulence are developed: The sound scattering cross-section for von Karman spectra of temperature and wind velocity fluctuations is calculated; the rigouros theory of line-of-sight sound propagation in an atmosphere with Kolmogorov, Gaussian and von Karman spectra of temperature and wind velocity fluctuations is developed; a new theoretical formulation of the interference of the direct wave from source to receiver and that reflected from the ground in a turbulent atmosphere is presented; the sound scattering cross-section in an atmosphere with arbitrary profiles of temperature and wind velocity is calculated; some predictions of the modern theory are verified experimentally; correct wide-angle parabolic equations for sound waves in a turbulent atmosphere are derived and used for numerical simulations of sound propagation.

The modern theory has already been adopted by scientists for calculations of sound propagation in turbulent media and as a basis for development of new acoustic remote sensing techniques of the atmosphere and ocean in several countries and organizations including the U.S. Army Research Laboratory.

14. SUBJECT TERMS
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Enclosure 1

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DEVELOPMENT OF THE MODERN THEORY OF SOUND PROPAGATION IN THE TURBULENT ATMOSPHERE

FINAL PROGRESS REPORT

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NOVEMBER 30, 1998

U.S. ARMY RESEARCH OFFICE
GRANT No DAAHO4-95-1-0593

NEW MEXICO STATE UNIVERSITY

1 STATEMENT OF THE PROBLEM STUDIED

The main task of the grant was to develop a modern theory of sound propagation and scattering in the turbulent atmosphere. Specific tasks 1 – 6 of the grant are listed below in section 2. Development of the modern theory of sound propagation in the turbulent atmosphere can significantly improve the performance of the U.S. Army acoustical systems indented for source detection, ranging and recognition. Previous theories do not allow calculation of many important statistical characteristics of a sound field and contain several incorrect results.

2 SUMMARY OF THE MOST IMPORTANT RESULTS

As a result of accomplishment of the grant, the foundations of the modern theory of sound propagation and scattering in a homogeneous and isotropic atmospheric turbulence have been developed. Accomplishment of the specific tasks of the grant are presented below. Furthermore, it has been worthwhile to extend the scope of the grant somewhat. First, we have systematically summarized results obtained in the modern theory in a book [1]. (The corresponding references are presented in section 3, List of publications.) This provides national and world-wide transfer of the results obtained towards accomplishment of the grant. Secondly, on the basis of the wide-angle parabolic equations derived in [7,8] we did numerical simulations of sound propagation in the turbulent atmosphere which were not planned originally (see task 6).

The modern theory provides new equations for the most often used statistical moments of a sound field propagating in a turbulent atmosphere with arbitrary spectra of temperature and wind velocity fluctuations. Furthermore, this theory presents calculation and detailed analysis of these statistical moments for the Kolmogorov, Gaussian and von Karman spectra of temperature and wind velocity fluctuations.

One of the main results of the modern theory is that it has clearly shown a difference between temperature and wind velocity contributions to the statistical moments of a sound field. In the previous theories these contributions are incorrectly assumed to be the same.

Some predictions of the modern theory have been verified experimentally. It has already been adopted by scientists for calculations of the statistical moments of a sound field and for developing new remote sensing techniques of the atmosphere and ocean in several countries and organizations

including the U.S. Army Research Laboratory.

Specific tasks of the grant and their accomplishment:

Task 1 To calculate the sound scattering cross-section $\sigma(\theta)$ for the von Karman spectra of temperature and wind velocity fluctuations.

Accomplishment:

The sound scattering cross-section $\sigma(\theta)$ is calculated for the von Karman spectra of temperature and wind velocity fluctuations [11,14]. It is shown that in limiting cases this scattering cross-section coincides with those calculated for the Kolmogorov and Gaussian spectra.

Task 2 To develop the modern theory of line-of-sight sound propagation in the turbulent atmosphere. We plan to present equations for statistical moments of plane and spherical waves propagating in the turbulent atmosphere with arbitrary spectra of temperature and wind velocity fluctuations. On the basis of this equations, we will calculate sound field statistical moments for the Kolmogorov, Gaussian and von Karman spectra.

Accomplishment:

The modern theory of line-of-sight sound propagation through homogeneous and isotropic atmospheric turbulence is developed [1,3-6,14-21]. For line-of-sight sound propagation, the most often used statistical moments of a sound field are the variances of log-amplitude and phase fluctuations, the correlation functions of log-amplitude and phase fluctuations, the mean sound field, and the coherence function. Equations for these statistical moments for plane and spherical waves are derived for arbitrary spectra of temperature and wind velocity fluctuations. Then, these statistical moments are calculated and analyzed in detail for the Kolmogorov, Gaussian and von Karman spectra.

Task 3 To derive the equation for mean intensity I of the sound field which is the sum of direct and ground-reflected waves in the atmosphere with arbitrary spectra of temperature and wind velocity fluctuations. Using this equation, we plan to calculate I for the Kolmogorov, Gaussian and von Karman spectra.

Accomplishment:

An equation for the mean intensity I of a sum of the direct wave from source to receiver and that reflected from the ground in an atmosphere with temperature and wind velocity fluctuations is derived [9]. This equation is valid for arbitrary spectra of temperature and wind velocity fluctuations. Using this equation, the mean intensity I is calculated and studied in detail for the Kolmogorov, Gaussian and von Karman spectra of temperature and wind velocity fluctuations.

Task 4 To develop the first theory of sound scattering into the refractive shadow zone. We plan to derive the equations for the mean intensity I, and the transverse Γ_t and longitudinal Γ_l coherence functions of the sound field scattered into the shadow zone in the atmosphere with arbitrary spectra of temperatures and wind velocity fluctuations. On the basis of these equations, we plan to calculate I, Γ_t and Γ_l for the Kolmogorov, Gaussian and von Karman spectra.

Accomplishment:

When we were doing other tasks of the grant, a theory of sound scattering into the refractive shadow zone was developed by K. Gilbert, X. Di and R.Korte (7th International Symposium on Long Range Sound Propagation, Lyon, 1996, p.373-389). According to this theory, the mean acoustic energy scattered into the refractive shadow zone is approximately proportional to a product of the sound scattering cross-section and the effective scattering volume. Therefore, our calculations of the sound scattering-cross section for the von Karman spectra of temperature and wind velocity fluctuations [11,14], see task 1, are also valuable for accomplishment of the task 4. Furthermore, for the first time we developed a correct theory which allows calculation of the sound scattering cross-section in the stratified moving atmosphere [2,10]. On the basis of this theory we numerically studied the effects of the vertical profiles of temperature and wind velocity on the sound scattering cross-section.

Task 5 To compare the theoretical results obtained with experimental and numerical ones presented in the literature.

Accomplishment:

Some predictions of the modern theory of sound propagation in random moving media have been verified for the cases of sound propagation through a turbulent jet [4,12] and in the turbulent atmosphere [6]. D. Irio and D. Farmer (J. Acoust. Soc. Am., V. 103, p.321-329, 1998)

verified some of these predictions for the case of sound propagation in the turbulent ocean, and V. Mellert and B. Schwarz-Roer (7th International Symposium on Long Range Sound Propagation, Lyon, 1996, p.391-405) did such verification for line-of-sight sound propagation in the turbulent atmosphere. Numerical simulations [8,13] of sound propagation in the turbulent atmosphere, which are performed using wide-angle parabolic equations derived, in limiting cases coincide with those known in the literature.

Task 6 To derive a correct starting equation for numerical simulation of sound propagation in the turbulent atmosphere.

Accomplishment:

Correct starting equations for analytical and numerical studies of sound propagation in the turbulent atmosphere are derived and compared with those known in the literature [1,7,8,13]. In particular, we derived correct wide-angle parabolic equations for sound waves in inhomogeneous moving media [7,8]. It was also worthwhile to extend a scope of this task and to do numerical simulations of sound propagation in the turbulent atmosphere [8,13] based on the wide-angle parabolic equations derived.

3 LIST OF ALL PUBLICATIONS SUBMITTED OR PUBLISHED UNDER SPONSORSHIP OF THE ARO GRANT No DAAHO4-95-1-0593:

- Books

1 Chapters: *6. Random inhomogeneities in a moving random medium*, and *7. Statistical moments of the sound field in a moving random medium* from the book:
Ostashev V.E. *Acoustics in Moving Inhomogeneous Media*, E & FN SPON (An Imprint of Thompson Professional), London (1997).

- Papers in peer-reviewed journals

2 V.E. Ostashev, G.H. Goedecke, R. Wood, H. Auvermann, and S.F. Clifford, Sound scattering cross section in a stratified moving atmosphere *J. Acoust. Soc. Am.* (submitted for publication).

3 Ostashev V.E., Brähler B., Mellert V. and Goedecke G.H., (1998) Coherence functions of plane and spherical waves in a turbulent medium with the von Karman spectrum of medium inhomogeneities, *J. Acoust. Soc. Am.* V.104, (2), Pt. 1, 727-737.

4 Ostashev V.E., Blanc-Benon Ph. and Juvé D. (1998), Coherence function of a spherical acoustic wave after passing through a turbulent jet, *Comptes Rendus de l'Académie des Sciences*, V.326 (1), serie II B, 39-45.

5 Ostashev V.E., Mellert V., Wandelt R. and Gerdes F. (1997) "Propagation of sound in a turbulent medium I. Plane waves", *J. Acoust. Soc. Am.*, V.102, (5), 2561-2570.

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7 Ostashev V.E., Juvé D. and Blanc-Benon P., "Derivation of a wide-angle parabolic equation for sound waves in inhomogeneous moving media", *Acustica*, V. 83, No 3, 455-460 (1997).

- Papers presented at conferences and symposia

8 L. Dallois, Ph. Blanc-Benon, D. Juvé and V.E. Ostashev, "A wide angle parabolic equation for sound waves in moving media", *Proc. 8th Intern. Symp. on Long Range Sound Propagation*, Penn State University (1998).

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14 Ostashev V.E., Goedecke G., Auvermann H. and Noble J., "Scattering cross section and variances of log-amplitude and phase fluctuations of a sound wave in a moving random medium with the von Karman spectrum of medium inhomogeneities", *J. Acoust. Soc. Am.* V. 100, No 4 (Part 2), 2747 (1996).

15 Ostashev V.E., Goedecke G., Bräler B., Mellert V. and Auvermann H., "Coherence functions of plane and spherical sound waves in the turbulent atmosphere with von Karman spectra of temperature and wind velocity fluctuations", *Proc. 7th Intern. Symp. on Long Range Sound Propagation*, Ecole Centrale de Lyon, France, 349-357 (1996).

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19 Brähler B., Ostashev V.E. and Wandelt R., "The coherence functions for plane and spherical waves in a moving random medium with the von Karman spectrum of medium inhomogeneities", *Acustica*, V. 82, Suppl. 1, S 163 (1996).

20 Gerdes F., Mellert V., Ostashev V.E. and Wandelt R., "Waves in moving random media with the Gaussian correlation function of medium velocity fluctuations", *Acustica*, V. 82, Suppl. 1, S 127 (1996).

21 Noble J.M. and Ostashev V.E., "New formulations for the scattering of sound in a moving random medium", *J. Acoust. Soc. Am.*, V. 98, No 5, Pt. 2, 2924 (1995).

4 LIST OF PARTICIPATING SCIENTIFIC PERSONAL

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